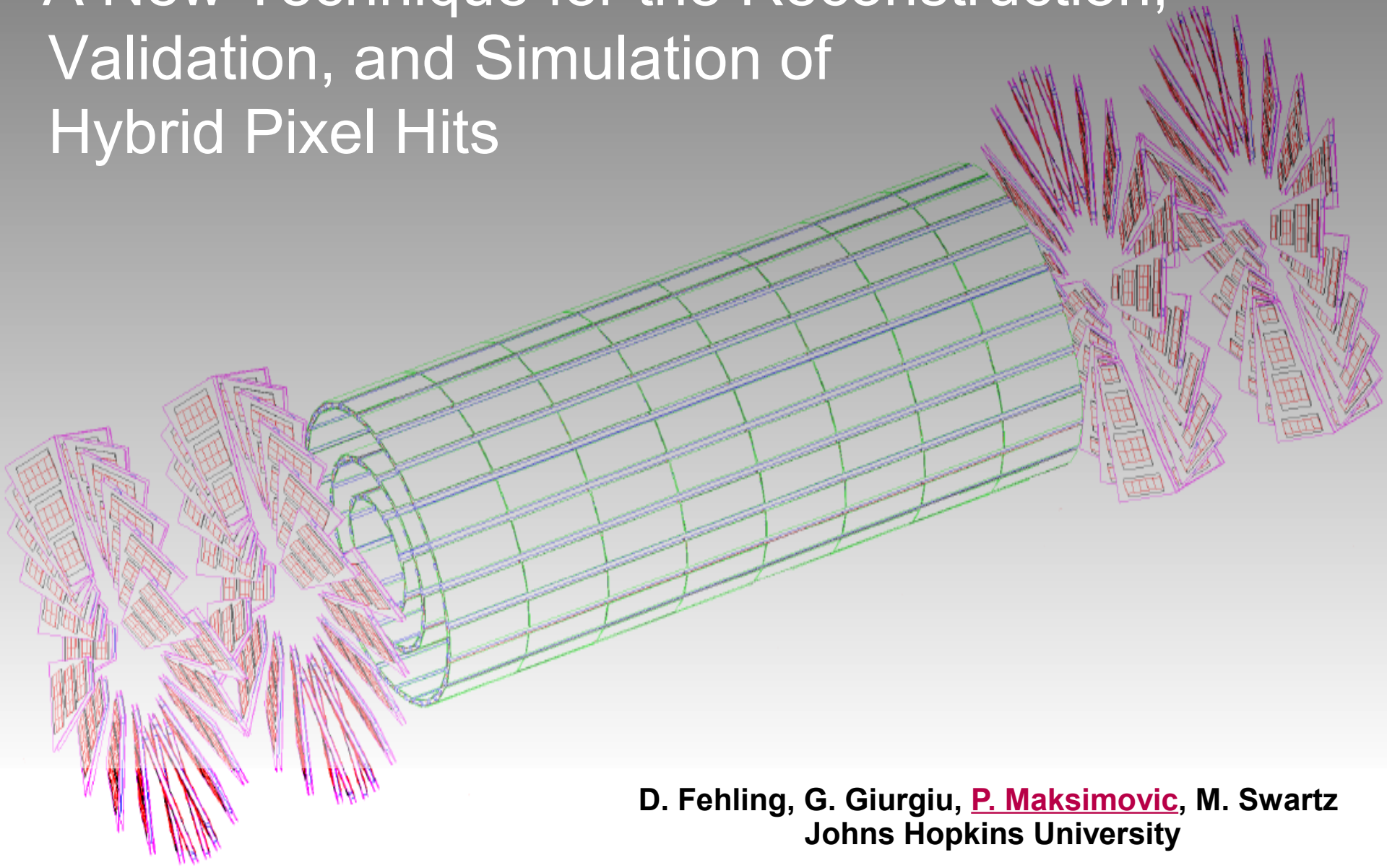


# A New Technique for the Reconstruction, Validation, and Simulation of Hybrid Pixel Hits



D. Fehling, G. Giurgiu, **P. Maksimovic**, M. Swartz  
Johns Hopkins University

V. Chiochia  
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# Outline

- PIXELAV = very detailed simulation of charge collection in silicon detectors

- developed to explain CMS test-beam data after irradiation

- “Observation, modeling, and temperature dependence of doubly peak edelectric fields in irradiated silicon pixel sensors.” M. Swartz et al. Oct 2005. Published in Nucl.Instrum.Meth.A565:212-220,2006.**

- New technique for position reconstruction in pixel detectors

- based on shapes predicted by PIXELAV

- for best performance, requires local incidence angles of the track  
(optimally used in the final track fit)

- documented in CMS (public) note:

- “A new technique for the reconstruction, validation, and simulation of hits in the CMS pixel detector.”**

- M. Swartz, D. Fehling, G. Giurgiu, P. Maksimovic, V. Chiochia (CERN) . CERN-CMS-NOTE-2007-033, Jul 2007.**

- Other uses:

- reject wrongly assigned hits (improve track seeding)

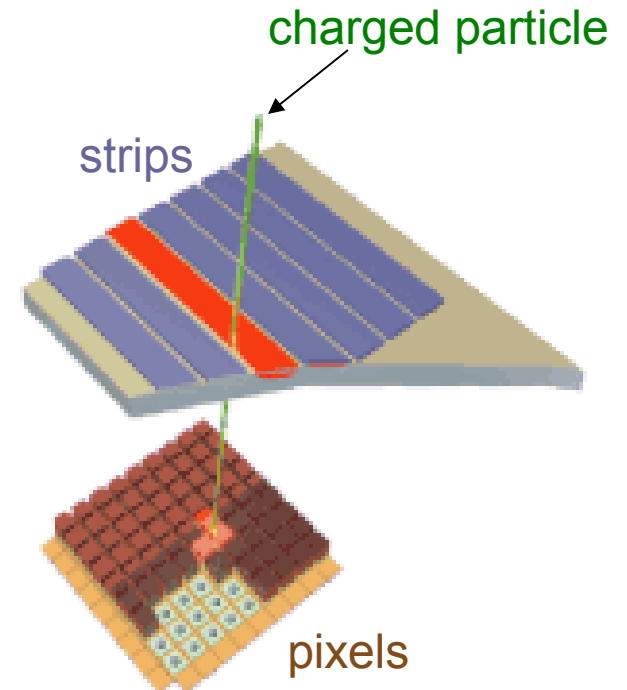
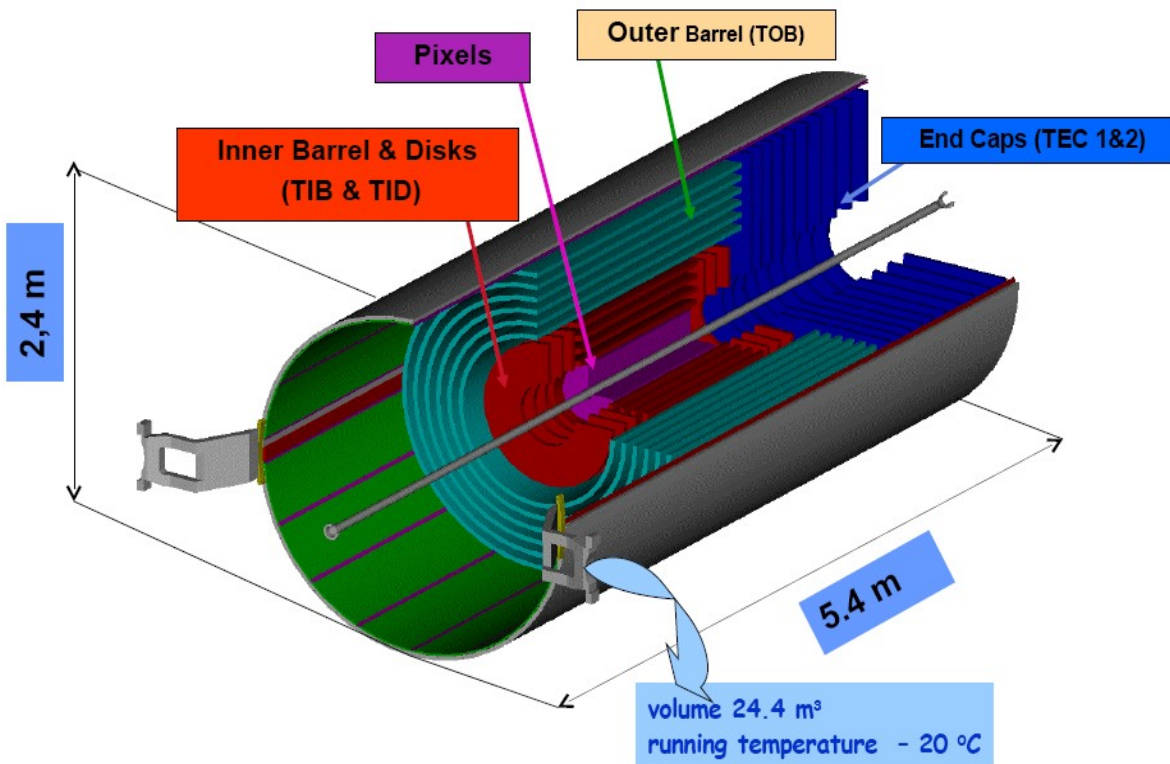
- split overlapping clusters (also reject some delta rays)

- realistic simulation of irradiation

# CMS Tracker System

- CMS tracker is all silicon:

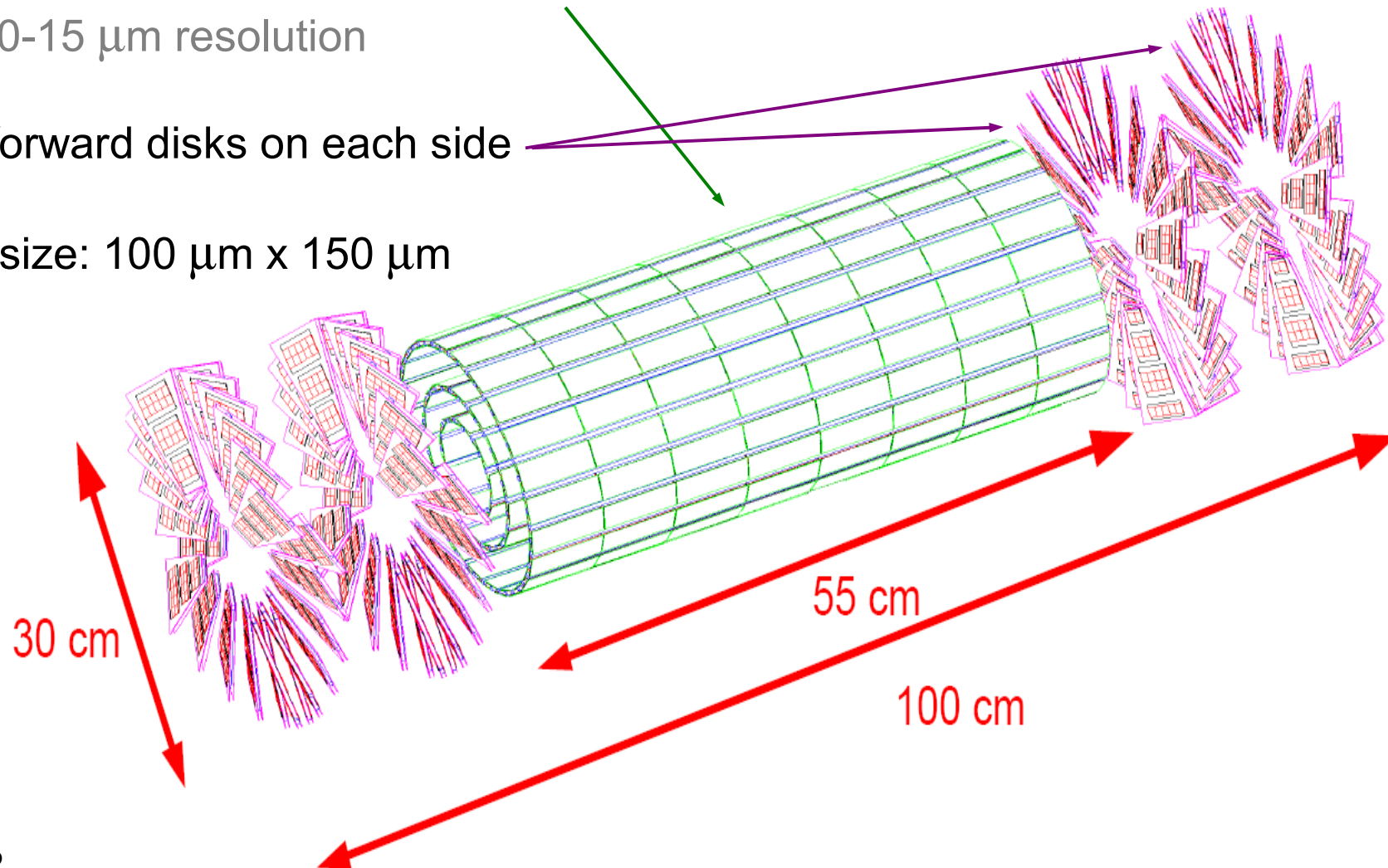
- strips
- pixels



charge collected by multiple pixels → clusters

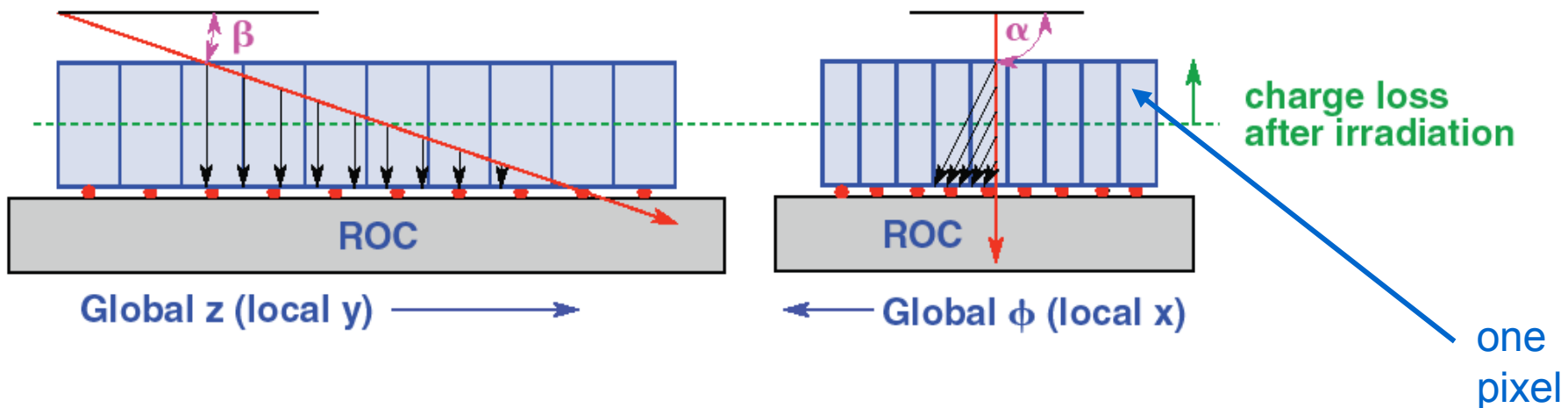
# CMS Pixel Detector

- Three barrel layers:
  - 4.3, 7.2, 11.0 cm from beam line
  - 10-15  $\mu\text{m}$  resolution
- Two forward disks on each side
- Pixel size: 100  $\mu\text{m}$  x 150  $\mu\text{m}$



# CMS Pixel Detector

- Pixel size:  $100\text{ }\mu\text{m} \times 150\text{ }\mu\text{m}$
- Cluster shape depends on “local incidence angles”  $\alpha$  and  $\beta$
- Length of each projection depends on  $\cot\alpha$  and  $\cot\beta$



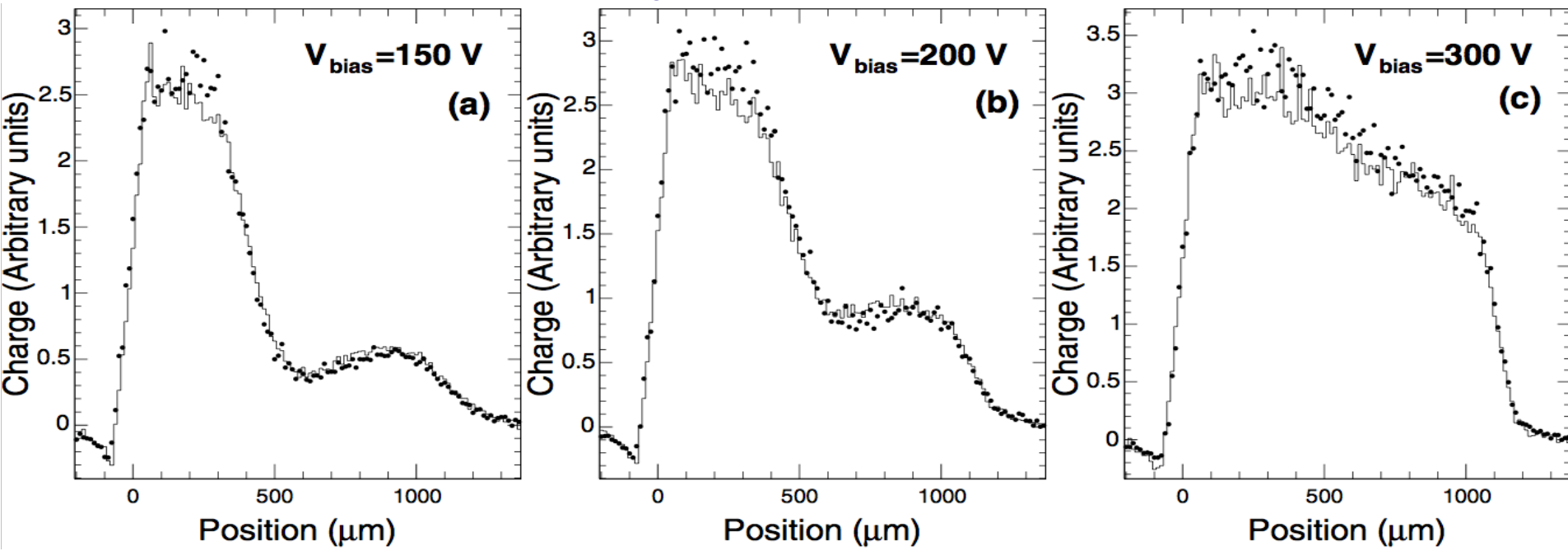
- Before irradiation:
  - charge sharing is uniform along  $z$  and  $\phi$
- After irradiation:
  - *defects* in the silicon lattice *trap charge* from one side of clusters
  - clusters become smaller, asymmetrically

*longer drift  $\rightarrow$  more charge trapped  $\rightarrow$  smaller signal*

# PIXELAV Realistic Simulation

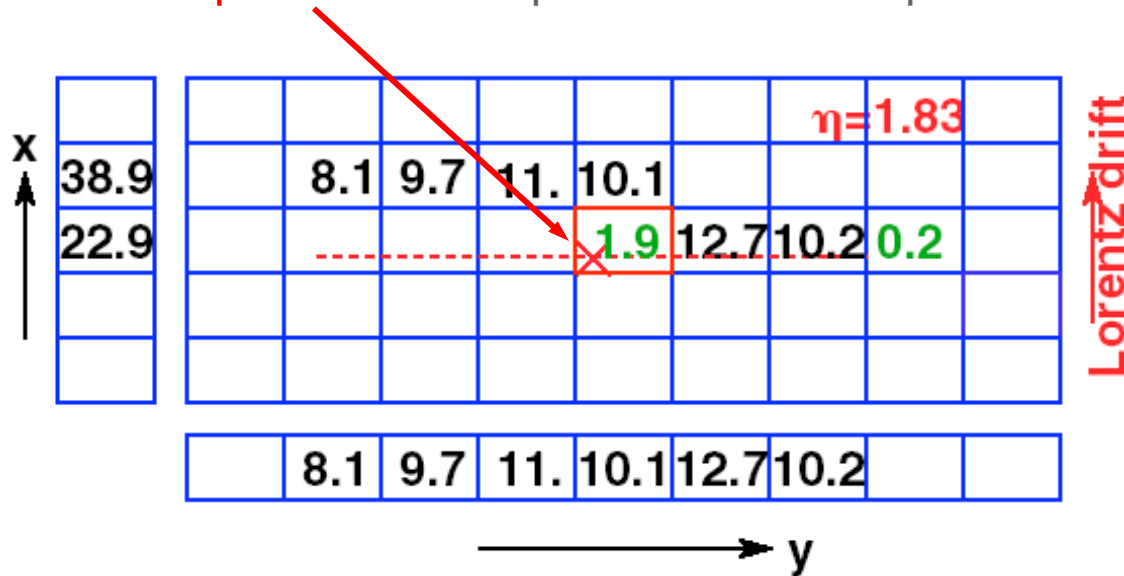
- **PIXELAV** = transport simulation of individual electrons
  - E-field modeling w/ TCAD 9.0
  - data well-described by tunable double-junction model from  $F = (0.5-6) \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$
  - *charge projections* of clusters in test-beam data (of both unirradiated and irradiated detectors) are *described extremely well*

Points = test beam data  
Histogram = Pixelav simulation



# Example of a Pixel Clusters

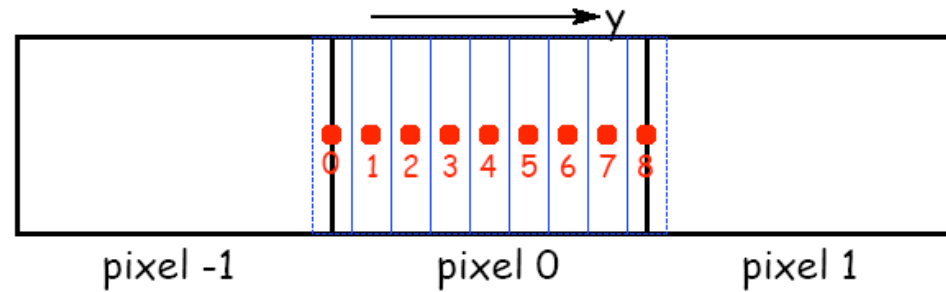
- Example *barrel* cluster (from a high  $\eta$  track)
  - green pixels are below threshold
  - note that **true hit position** is in a pixel which is not part of the cluster



- Making templates:
  - Use PIXELAV gives projections of average cluster shapes for all  $\alpha$  and  $\beta$
  - Only X and Y projections are encoded:
    - they are (roughly) independent
    - require less space

# Template Object

- A template object is a map of expected charge depositions for given local incidence angles  $\alpha$  and  $\beta$
- Charge deposited in a pixel is divided in 9 bins:



## Unirradiated Template

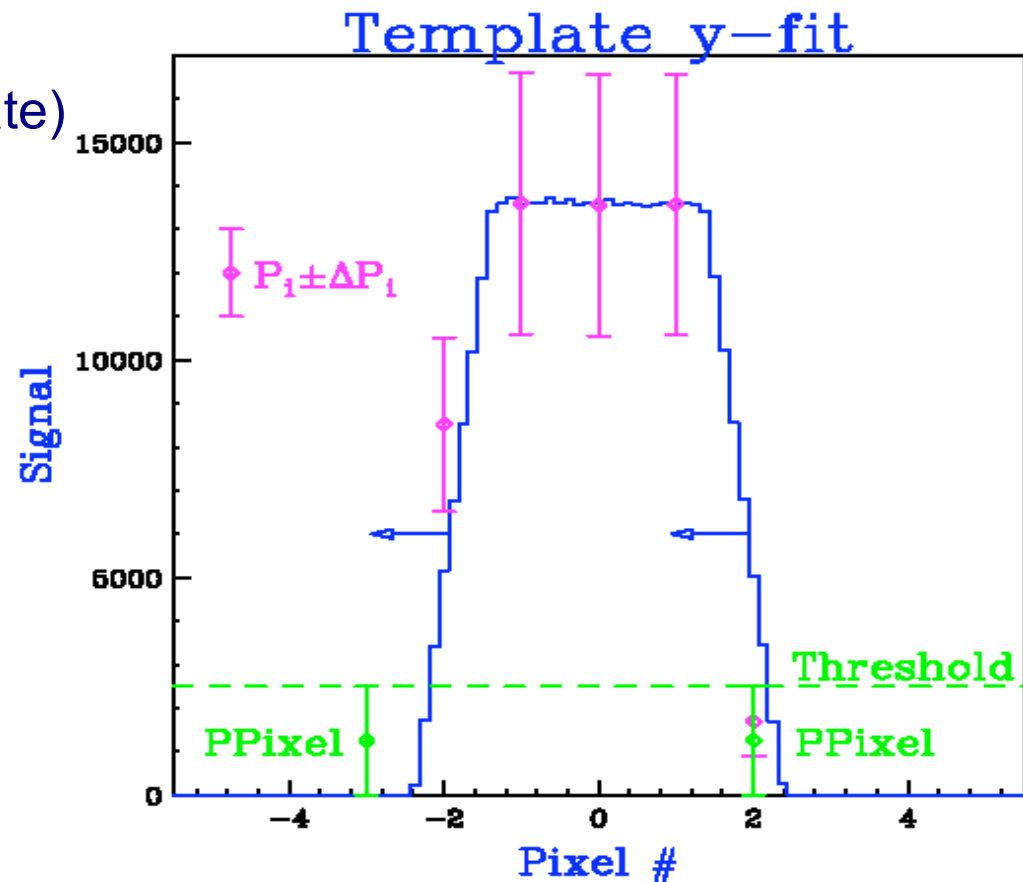
Bin	Px-6	Px-5	Px-4	Px-3	Px-2	Px-1	Px 0	Px+1	Px+2	Px+3	Px+4	Px+5	Px+6
0	.0	.0	.0	.0	11884.5	13587.8	13549.2	11913.7	.0	.0	.0	.0	.0
1	.0	.0	.0	.0	10198.0	13727.3	13592.2	13404.4	252.2	.0	.0	.0	.0
2	.0	.0	.0	.0	8512.6	13597.7	13559.3	13577.9	1688.0	.0	.0	.0	.0
3	.0	.0	.0	.0	6762.7	13607.2	13677.0	13601.3	3428.0	.0	.0	.0	.0
4	.0	.0	.0	.0	5165.2	13569.4	13603.1	13644.9	5039.3	.0	.0	.0	.0
5	.0	.0	.0	.0	3412.1	13718.7	13604.0	13630.6	6812.7	.0	.0	.0	.0
6	.0	.0	.0	.0	1703.1	13589.0	13566.5	13567.4	8556.2	.0	.0	.0	.0
7	.0	.0	.0	.0	216.7	13396.4	13685.1	13544.1	10208.5	.0	.0	.0	.0
8	.0	.0	.0	.0	.0	11884.5	13587.8	13549.2	11913.7	.0	.0	.0	.0

## $\Phi=6 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$ Template

Bin	Px-6	Px-5	Px-4	Px-3	Px-2	Px-1	Px 0	Px+1	Px+2	Px+3	Px+4	Px+5	Px+6
0	.0	.0	.0	.0	8741.4	8925.9	7156.1	5599.7	661.8	117.3	.0	.0	.0
1	.0	.0	.0	.0	7476.2	9160.4	7301.2	6194.2	872.6	148.9	.9	.0	.0
2	.0	.0	.0	.0	6160.6	9403.8	7423.7	6417.5	1429.4	187.5	9.6	.0	.0
3	.0	.0	.0	.0	4736.1	9578.0	7614.0	6610.0	2081.9	233.6	20.6	.0	.0
4	.0	.0	.0	.0	3432.4	9790.6	7814.7	6764.0	2789.8	291.1	34.0	.0	.0
5	.0	.0	.0	.0	2112.5	9944.1	8087.9	6894.2	3490.9	357.9	49.4	.0	.0
6	.0	.0	.0	.0	750.7	10174.1	8382.4	7018.6	4199.1	440.9	67.9	.0	.0
7	.0	.0	.0	.0	33.3	10014.0	8695.2	7053.7	4882.2	538.5	90.1	.0	.0
8	.0	.0	.0	.0	.0	8741.4	8925.9	7156.1	5599.7	661.8	117.3	.0	.0

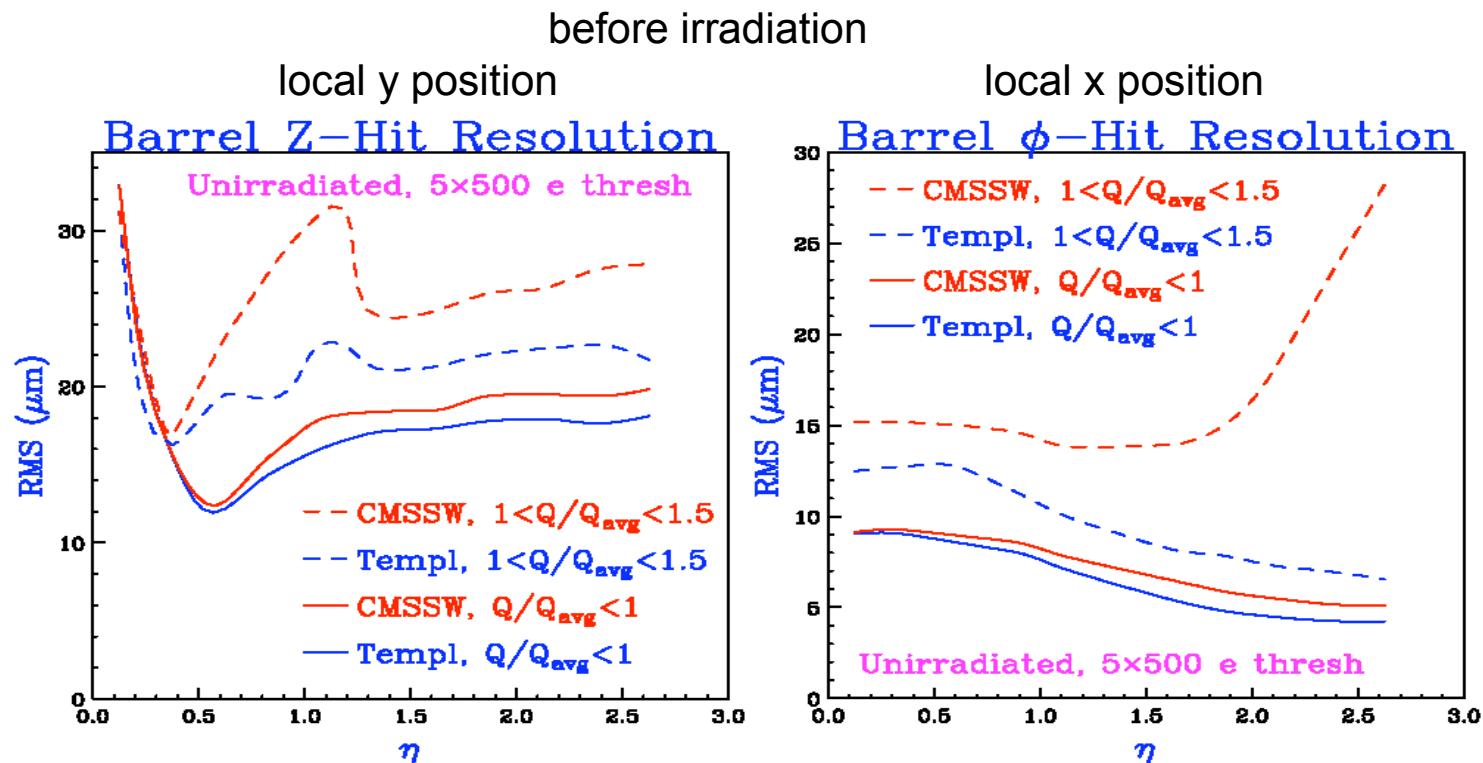
# Template Reconstruction Algorithm

- Cluster shape provides information for optimal hit reconstruction
- After irradiation, cluster shape still contains enough position information
- Given the track incident angles  $\alpha$  and  $\beta$ , find corresponding expected cluster shape (template)
- Do this separately for X and Y projection
- *Determine the hit position that minimizes  $\chi^2$  between template and cluster*



# Expected Template Performance

- PIXELAV comparison between **standard (red)** and **template (blue)** algos
- Before irradiation: *expect good resolution improvements*

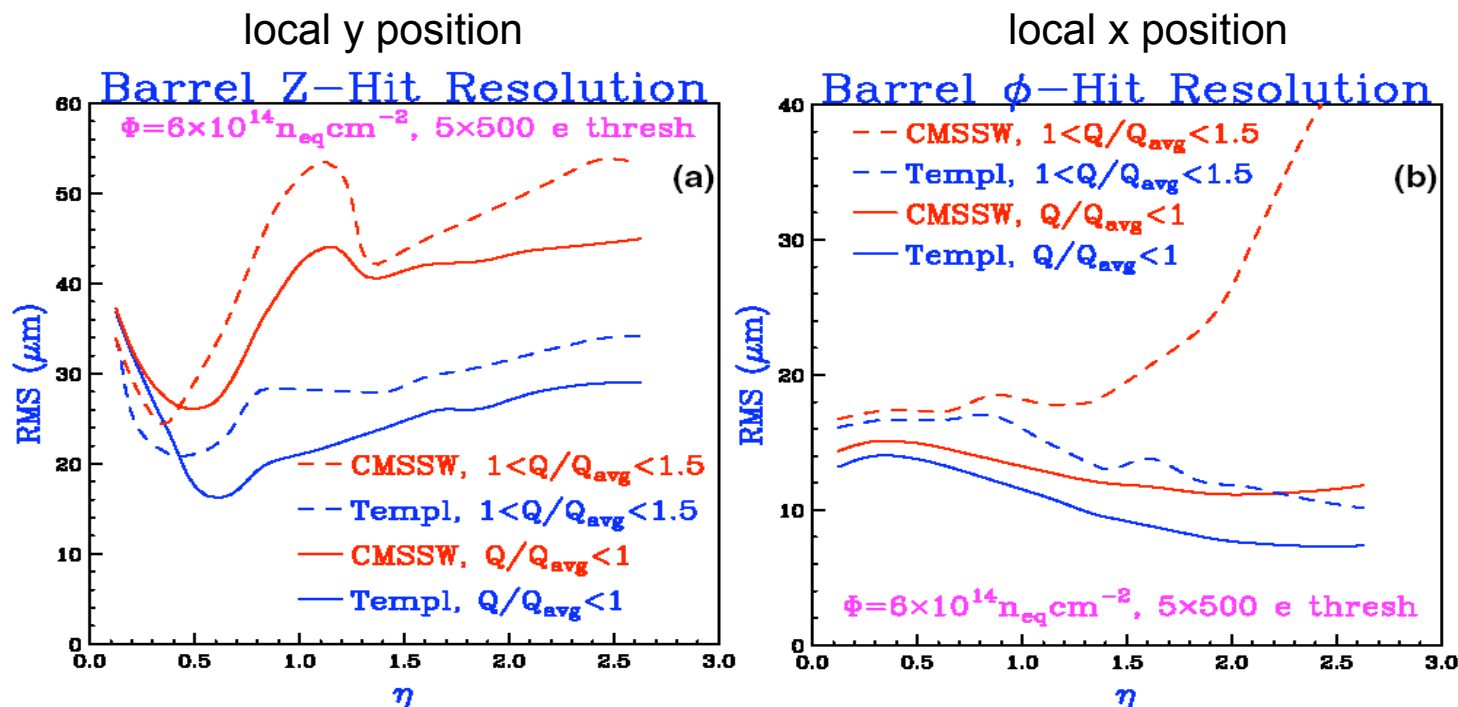


(here, CMSSW = standard CMS reconstruction)

# Expected Performance After Irradiation

- After irradiation: standard algorithm is much more affected than templates
- $\Rightarrow$  *template algorithm will perform much better and will have much smaller biases*

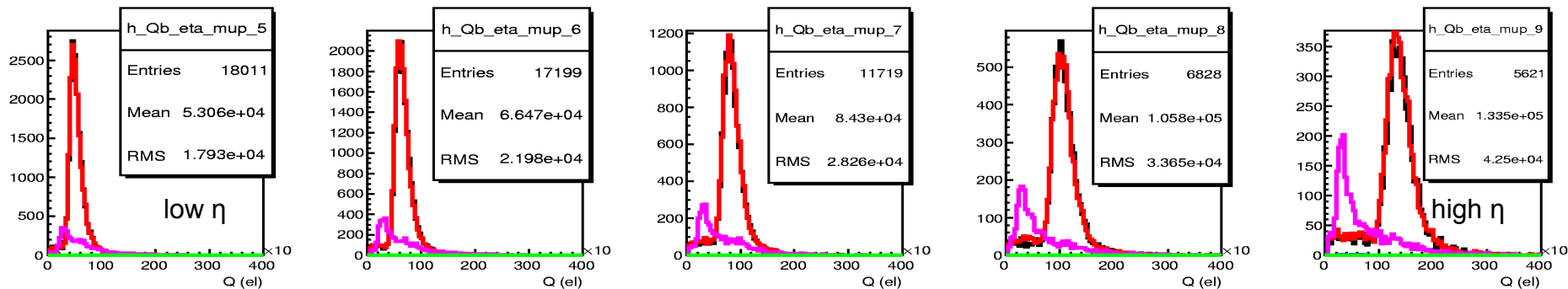
after irradiation



(here, CMSSW = standard CMS reconstruction)

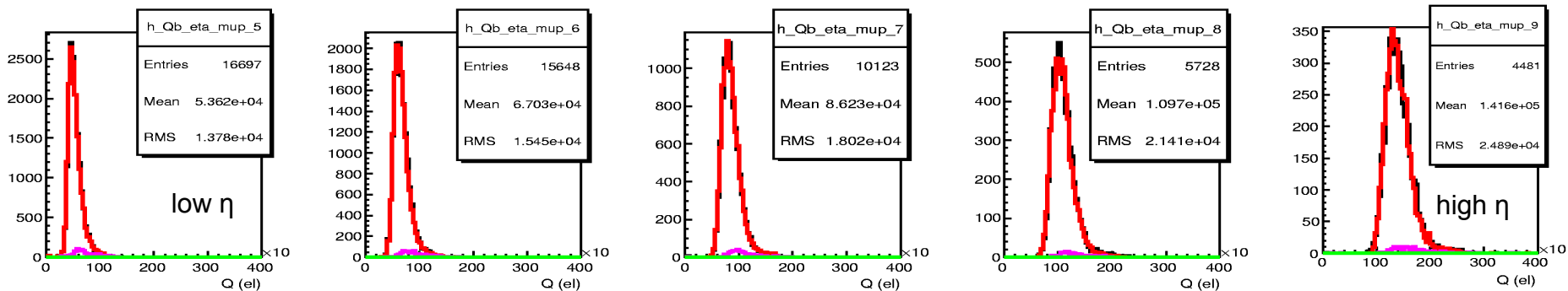
# Removing Low Charge Clusters

- Low charge clusters are produced by upstream delta-rays or edge clusters
- *Delta rays (magenta) can be removed using the  $\chi^2$  probability between the observed and expected cluster shapes*
- Cluster charge distributions produced by 10 GeV muons in different  $\eta$  bins:
  - black  $\rightarrow \mu^+$ , red  $\rightarrow \mu^-$ , magenta  $\rightarrow$  electrons (delta rays)

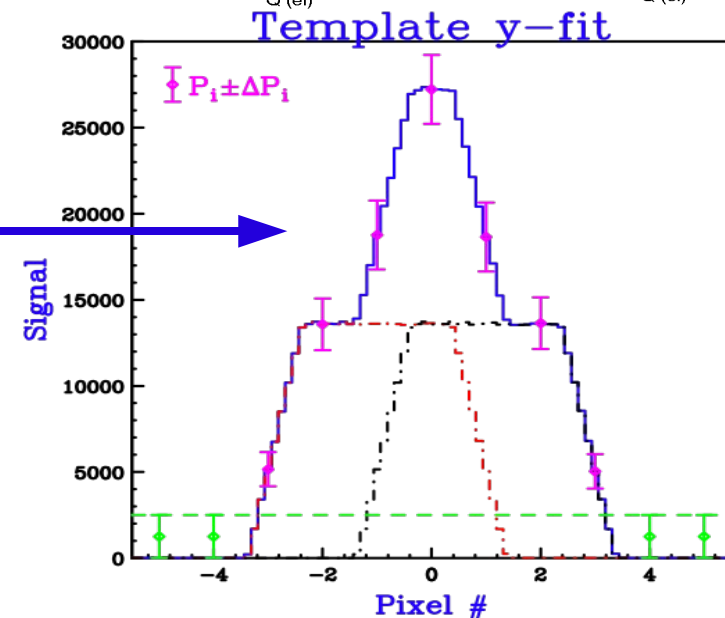


# Removing Low Charge Clusters (2)

- A hit probability cut of  $10^{-3}$  *removes most of delta-rays and edge clusters*
- Efficient: only  $\sim 1\text{-}2\%$  of true hits are removed



- Another approach: split clusters.
  - Developed for tracking in dense jets
  - Accidental benefit: *effective in removing delta rays as well!*

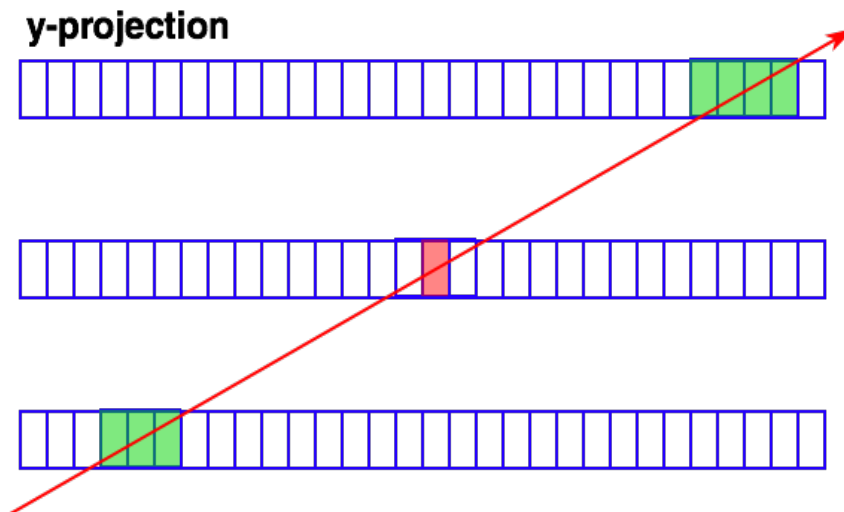


# Speed-up Tracking with Better Track Seeding

- In a dense hadronic environment, time of pattern recognition (tracking) is driven by the combinatoric of multiplets of hits
- At CMS, the default algorithm starts from pixel 'seed' and goes **outward**
- Pixel seed:
  - 2 or 3 pixel hits

- Template fit can help avoid wrong seeds:
  - run the template fit, cut on probability
  - will remove clusters that are inconsistent with the track hypothesis

**==> Speeds up tracking by almost x2!**



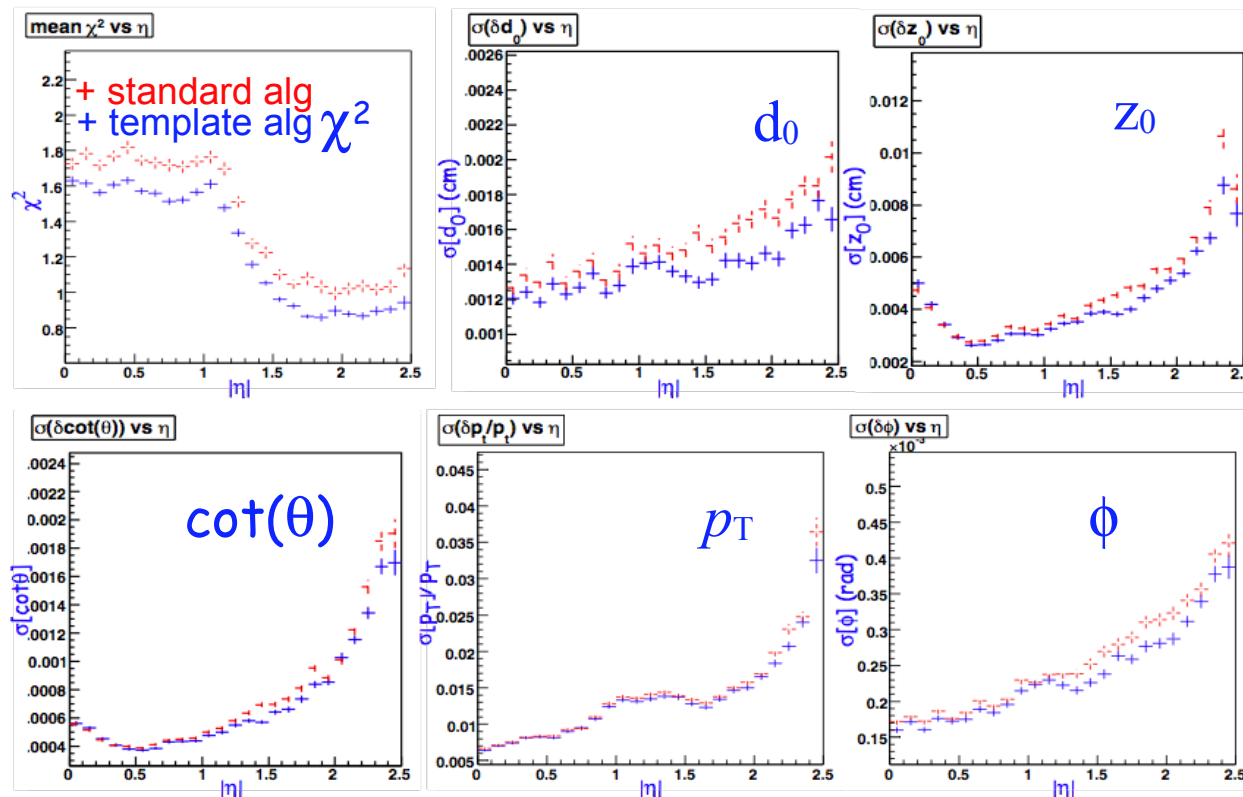
- Under study: remove dubious hits at the end, in 'outlier rejection'

# Simulating Irradiation Effects

- PIXELAV reproduces cluster shapes after irradiation extremely well
  - alas, too slow to run directly in CMS simulation!
- Default CMS charge deposition/collection is fast, but too idealized
- Compromise: use the default charge deposition/collection, but reweight using ratio of PIXELAV and average default simulation
  - default CMS simulation fluctuates the charge collection properly
  - radiation damage is taken into account
  - it's fast
- Main technical challenge was to manufacture 2D shapes from two 1D templates (along X and Y)

# Tracking Resolution with Template Reco.

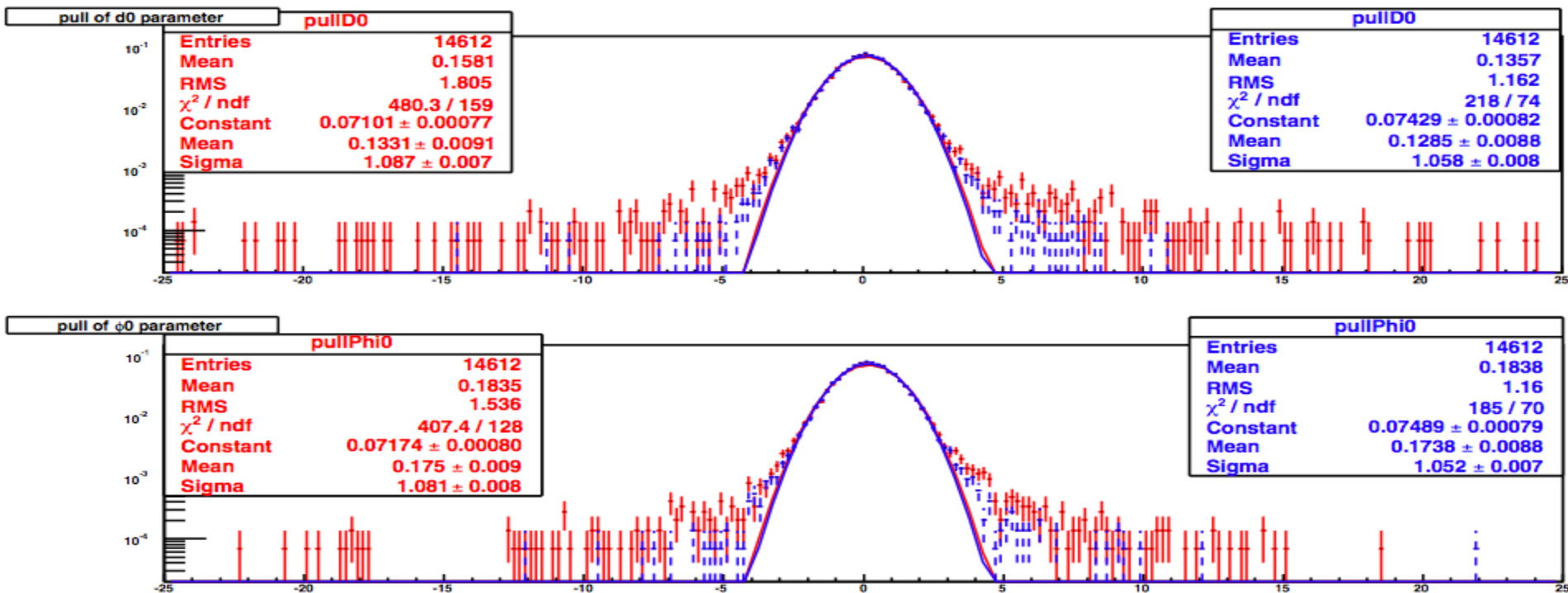
- Compare  $\chi^2$  and Gaussian width of track parameters' pulls



- Improved  $\chi^2$ , impact parameter ( $d_0$ ),  $Z_0$ ,  $\cot(\theta)$  and azimuth angle ( $\phi$ ) resolution especially at high- $\eta$  ranges

# Tracking Resolution with Template Reco.(2)

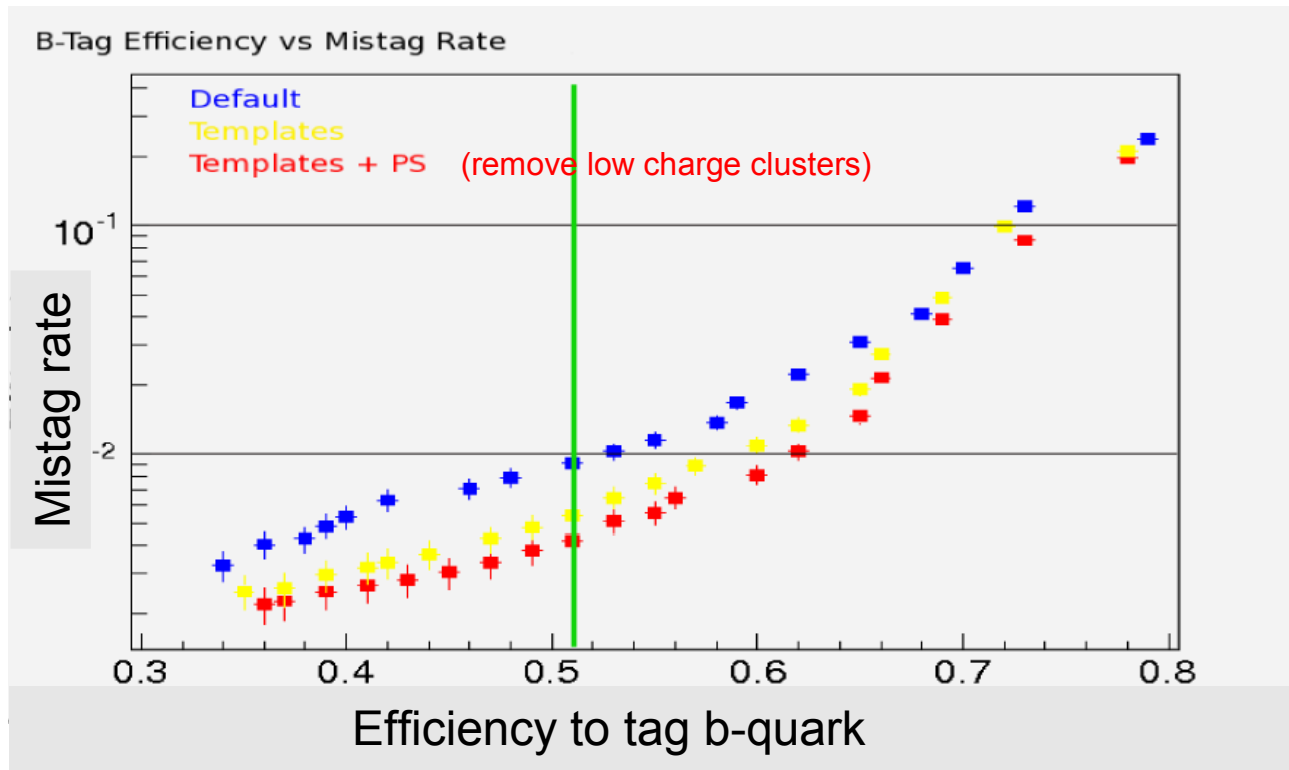
- Template algorithm *significantly reduces tails* in the pulls:



- Expect to see significant improvement in b-tagging, especially in mistag rate which is driven by tails!

# B-Tagging Using Template Hits

- B-tagging algo = based on the significance of impact parameter (IP)
- Run on generic QCD sample



- For b-tag efficiency of 50% the *mistag rate is reduced by a factor of 2*
- For a mistag rate of 1% the b-tag efficiency is better by 10%

# Conclusions

- A new method (template algorithm) that uses all available charge information has been developed
- Before radiation damage: improved hit resolution (also better errors)
- After radiation damage: the only option available!
- Improved b-tagging:
  - *Reduced b-tag mistag rate by factor of 2*
- By-product of the template method is the pixel hit probability
  - When used to clean track 'seeds' → *tracking time reduced x2!*
- Templates *can be used to simulate irradiated sensors*
  - By re-weighting simulated clusters